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RAINFALL HARVESTING SYSTEM DESIGN

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Rainfall Harvesting System Design [1]

By W. O. Ree, F. L. Wimberley, W. R. Gwinn, and C. W. Lauritzen[2]

Wherever rain falls on the earth's surface, a supply of water can be assured. However, it may be necessary to capture each raindrop before it evaporates or soaks into the ground and to store it for future use if a practical supply system is to be developed. This is the principle of the rainfall harvesting system discussed in this report.

Rainfall harvesting systems can be costly because they require impervious catchment areas and loss-proof storage tanks. Still, such a system could be the economic choice in a water-short area, where often the only alternative is to transport water from a water-abundant area. This is particularly true in the arid West. Rainfall harvesting systems should also be considered for water supply where water of higher quality than obtainable from other sources is needed. The Animal Husbandry Department of Oklahoma State University needed a mineral-free supply of water for cattle nutrition studies. The rainfall harvesting system described in this report was installed to test the suitability of water obtained. This installation provided the opportunity to observe rain trap performance and to obtain data for rain trap design.

THE RAIN TRAP

The water harvesting system consists of a butyl rubber liner on a sloping catchment area. A sketch of the catchment and reservoir is shown on figure 1. The runoff from the catchment drains into a reservoir lined and covered with butyl rubber. Construction details are not described because these have been discussed previously by Lauritzen.[3] An opening is provided in the liner at the bottom of the reservoir for a pump intake. The area of the catchment is 2,504 square feet, and the capacity of the reservoir is approximately 19,000 gallons. The system was expected to permit the withdrawal of about 200 gallons of water daily.

A runoff measuring flume between the catchment and the reservoir provides a record of the flow from the catchment. Recording rain gages were placed adjacent to the catchment. These instruments are a part of the experimental setup and would not be a part of a regular rainfall harvesting system.

Figure 2 is a photograph of the flow measuring arrangement. A 9-inch H-flume is inside the box at the step in the floor of the box. Suitable baffling in the appraoch box breaks up the jet from the entrance pipe and stills the water before it reaches the H-flume. The lower part of the box receives the water from the H-flume and delivers it to the exit pipe and thence to the storage reservoir. This flow-measuring device was calibrated in the hydraulic laboratory. An FW-1 water level recorder provided with 6-hour gears is located in the instrument shelter above the box.

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[1] Contribution from the Soil and Water Conservation Research Division, Agricultural Research Service, U.S. Department of Agriculture, in cooperation with the Oklahoma Agricultural Experiment Station, Stillwater.

[2] Research Investigations Leader, hydraulic engineering technician, and research hydraulic engineer, USDA, Stillwater, Okla., and soil scientist (deceased), USDA, ARS, Logan, Utah, respectively.

[3] Lauritzen, C. W. Butyl–for the collection, storage, and conveyance of water. Utah Agr. Expt. Sta. Bul. 465, 41 pp., illus. 1967.

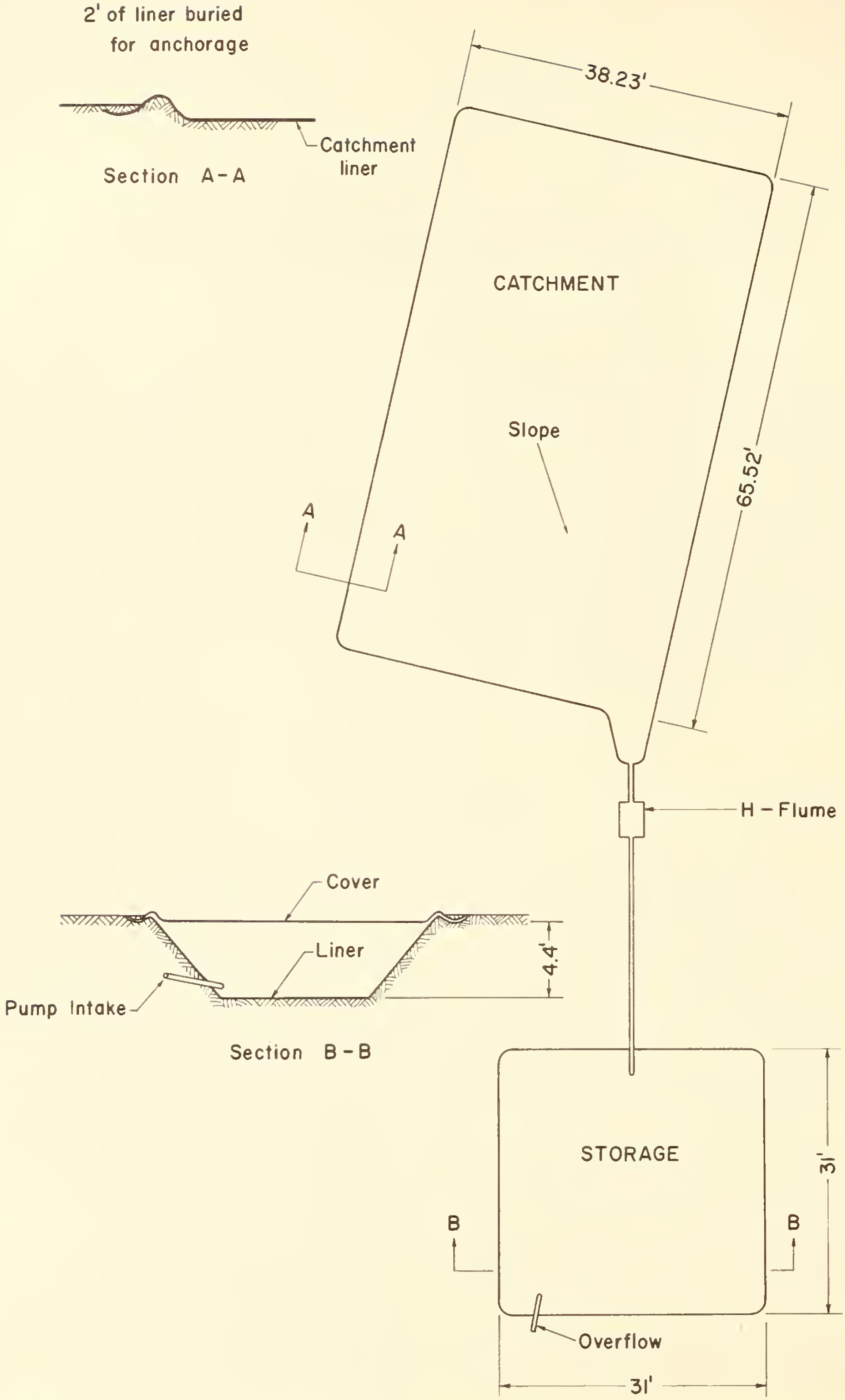

Figure 1.–Rainfall harvesting system near Stillwater, Okla. The catchment and tank liners are made of butyl rubber.

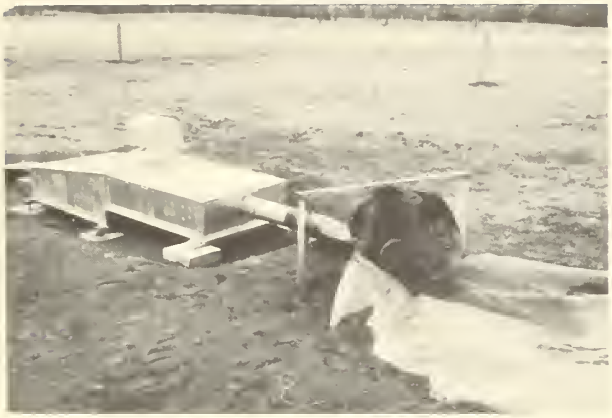

Figure 2.--Runoff measuring device for the rainfall harvesting system. A 9-inch H-flume inside the box measures the runoff.

VOLUME OF RUNOFF

Rainfall and runoff were measured for a 25-month period ending December 31, 1966. Runoff volumes were converted to inches of runoff from the catchment area and compared with the rainfall. This comparison is shown on figure 3, a plotting of runoff depths versus rainfall depths for the individual storms. With few exceptions, the equality of the rainfall and runoff are immediately evident from an inspection of figure 3. These exceptions occurred during the winter when runoff exceeded rainfall. This was probably due to snow drifting onto the catchment. Rainfall and runoff volumes for selected periods are shown in table 1. The good agreement between the two for nonwinter periods was experienced for both years of operation.

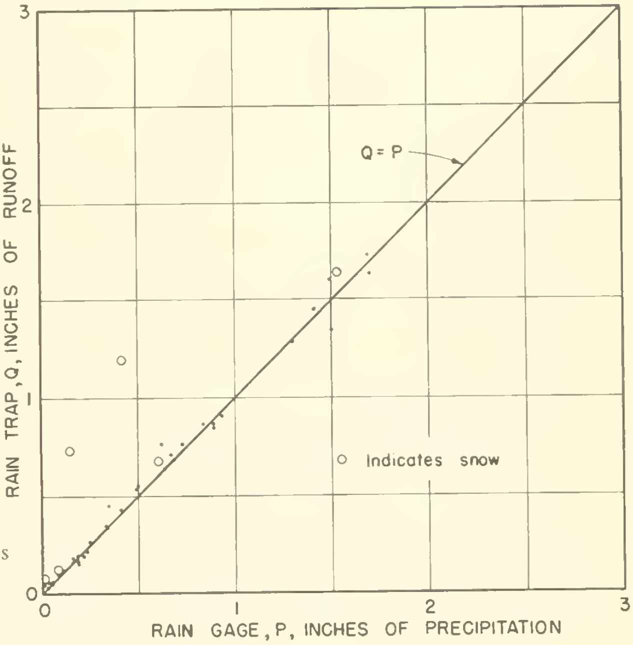

Figure 3.--Runoff volume versus precipitation volume for storms over the water harvesting installation near Stillwater, Okla.

Table 1. Comparison of precipitation and runoff amounts for winter and nonwinter periods

Period	Precipitation	Runoff
	Inches	*Inches*
Winter (12/3/64 to 3/25/65)	2.74	4.12
Nonwinter period[1] (4/2/65 to 10/18/65) .	13.16	13.63
Winter (12/23/65 to 2/28/66 and 12/22/66 to 12/31/66)	4.35	6.24
Nonwinter period[2] 11/4/65 to 12/15/65 and 3/1/66 to 12/7/66)	17.96	18.41

[1] Excluding 4 storms, during which loss of runoff was caused by overflow.
[2] Excluding 1 storm affected by high winds.

RATE OF RUNOFF

Rainfall intensities were compared with rates of runoff. Good agreement was generally obtained between the shape of the rainfall histogram and the runoff hydrograph. Three of these comparisons are shown on figure 4.

Rainfall intensity and runoff rates for the storm of August 18, 1966, showed excellent agreement. This same quality of agreement was not obtained for the storm of June 5, 1966. High winds during this storm whipped some of the water on the catchment over the boundary dikes. The volume of runoff did not suffer much due to this wind, but the peak rate was considerably reduced. The rainfall peak rate is shown for a 2-minute duration, but this period may be too short.

Generally, good agreements were obtained between runoff rates and the related rainfall intensity for a 5-minute duration (fig. 5)

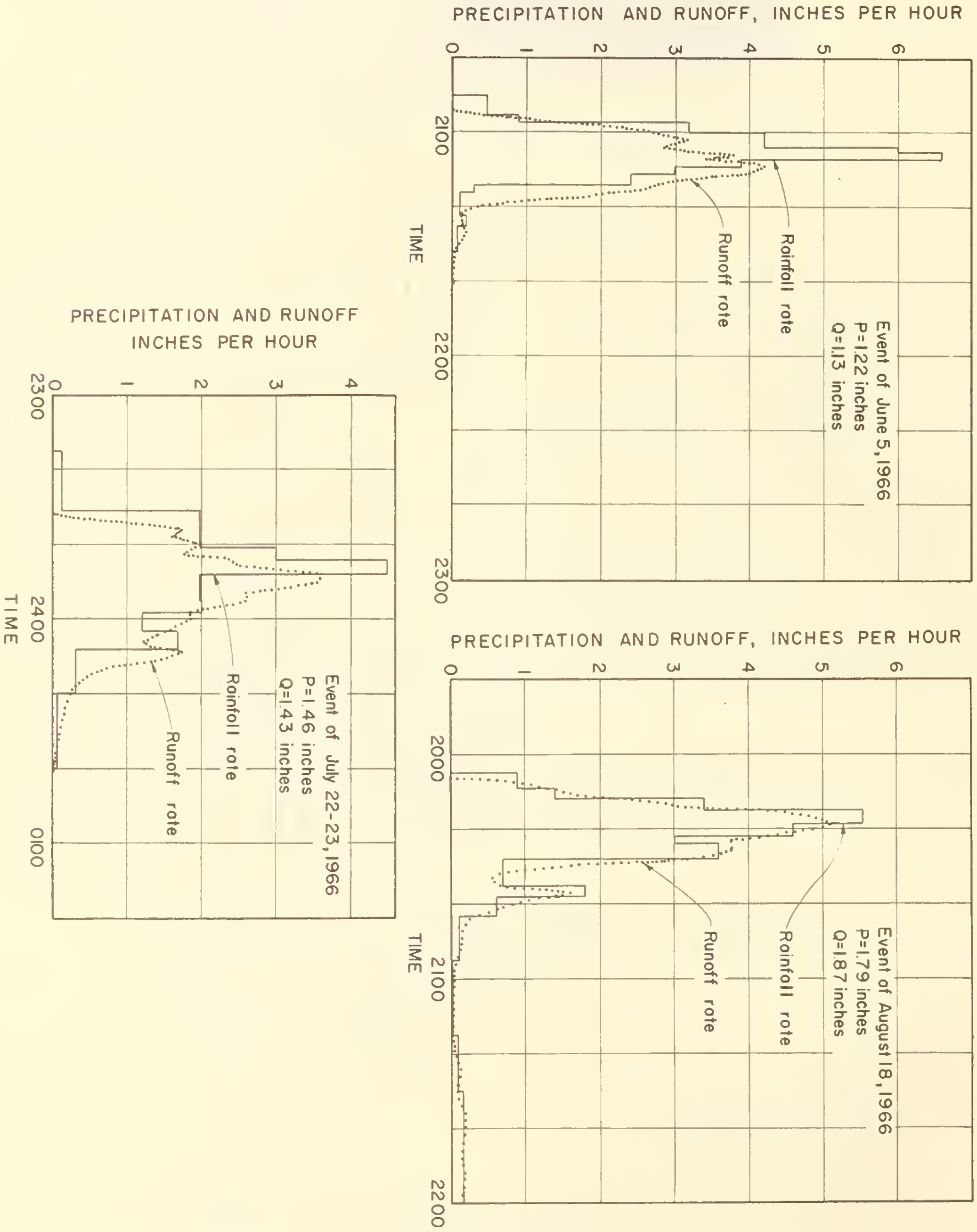

Figure 4.–Histograms and hydrographs for selected storms on the water harvesting installation near Stillwater, Okla.

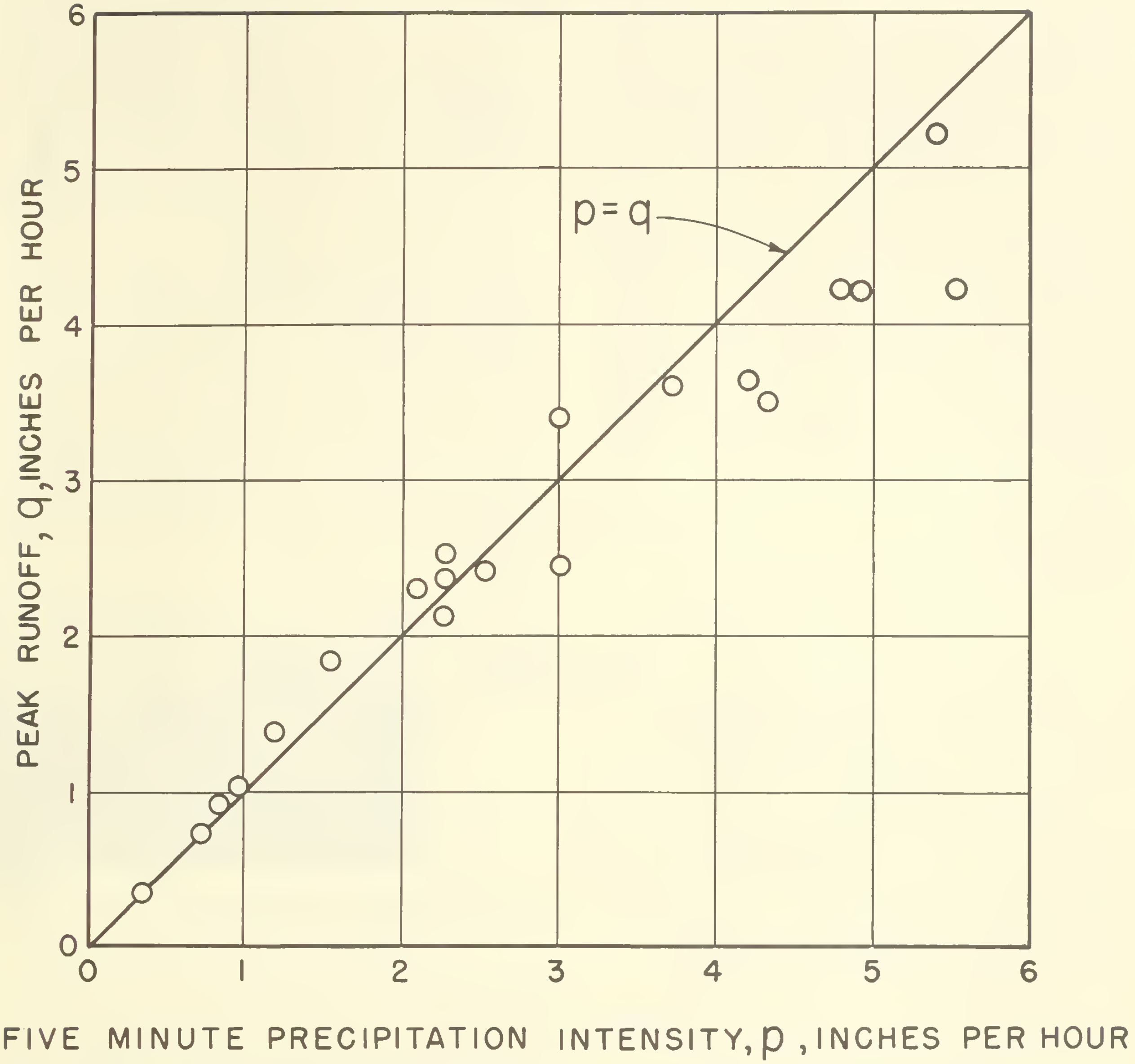

Figure 5.–Peak runoff rate versus related 5-minute precipitation intensity for selected storms over the water harvesting installation near Stillwater, Okla.

WATER QUALITY

Water from the reservoir was collected on November 24, 1967,[4] and analyzed for mineral constitutents by the U.S. Geological Survey. The findings are given below. The relatively high zinc concentration may be due to airborne pollutants.

	Parts per million
Strontium (Sr)	0.0
Lithium (Li)	.0
Silica (SiO_2)	.7
Chromium (Cr^6)	.00
Iron (Fe)	.01
Lead (Pb)	.00
Manganese (Mn)	.03
Zinc (Zn)	1.4
Copper (Cu)	.00
Calcium (Ca)	.9
Magnesium (Mg)	.2
Sodium (Na)	.3
Potassium (K)	.0
Oxygen consumed	.6
Bicarbonate (HCO_3)	2
Carbonate (CO_3)	0
Sulfate (SO_4)	5.4
Chloride (Cl)	.1
Fluoride (F)	.2
Nitrate (NO_3)	.0
Phosphate (PO_4)	.0
Boron (B)	.0
Dissolved solids	
Calculated	--
Residue on evaporation at 180°C	9
Hardness as $CaCO_3$	5
Noncarbonate hardness as $CaCO_3$	--
Alkalinity as $CaCO_3$	--
Specific conductance (micromhos at 25°C.)	21
pH	5.0

Tests for bacterial contamination, made by the Microbiology Department of Oklahoma State University, showed the water to be contaminated with feces and not fit for human consumption unless filtered and chlorinated.

WIND EFFECTS

During the first year after installation, the catchment liner would billow in a high wind (fig. 6). The two standing humps in figure 6 are about 5 feet high.

Three small holes were found in the liner near the edge. One of these was over a hard clod. Wind blowing the liner over this clod probably caused the wearing and rupturing of the liner at this point. The three holes were repaired with rubber patches.

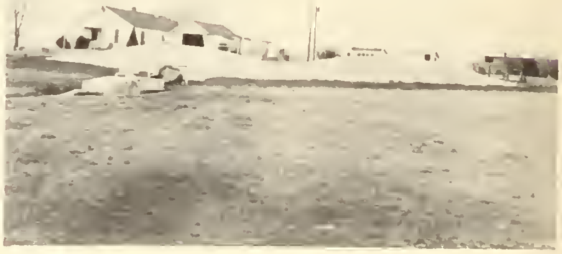

Figure 6.–The butyl rubber liner for the rainfall catchment is billowing in an 18-mile an hour wind.

RODENT DAMAGE

In one night, 14 holes were torn in the liner, the largest hole being 8 inches by 18 inches. This damage may have been done by skunks after mice which had made a home under the liner. Placing a poison under the liner to kill the mice would have been hazardous because of the possibility of contaminating the runoff water. The holes were patched with cold patch. No damage has occurred since.

RAIN TRAP PERFORMANCE

The rain trap has been in place for 5 years, and the butyl rubber liners are still in good condition. If it were not for the patches covering holes torn by animals, the liners would be nearly as good as new.

Billowing of the catchment liner, which occurred to great extremes during the first year, diminished considerably in height during subsequent years. Billowing was probably caused by uplift forces created by the wind stream rising over the downwind dike. However, if this was the cause, why did the billowing diminish with time? Possibly, the velocity profile of the wind near the ground surface was altered by grass which began to grow on the outside face of the dike.

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[4] Collected from ARS rain trap in Noble County, T. 20 N., R. 1 E., sec. 31, NW¼. Sample was pumped from a point about 8 or 10 inches above the bottom of the tank.

The volume of runoff slightly exceeded the volume calculated as the product of the catchment area and the depth of rainfall recorded by the rain gage. This excess of actual runoff usually occurred during the winter. The assumption that runoff is equal to 100 percent of gage rainfall is satisfactory for design purposes.

The overflow of runoff at the entrance to the collector funnel indicates that attention must be given to expected runoff rates. In this experiment, the collection and measurement of all water discharged by the catchment were necessary if complete information was to be obtained. In field installations, overflow at the collector could be permitted if done safely, provided this did not reduce water supply below design levels and that savings could be effected in the size and cost of the collecting and conveying components. The capacity design of these components requires information on the rates of rainfall for short durations. It was thought that the 5-minute period, the shortest period usually reported in storm reports, is not short enough, because times of concentration for catchments may be less than 5 minutes. The good agreement between runoff rate and average rainfall intensity for 5-minute periods is explained in part by the temporary storage of runoff in the collecting and measuring system. Since all of this storage would not be a part of a field system, the use of the 5-minute intensity for rainfall rate might not be conservative. Until short duration rainfall data are available, the designer will need to employ a judgment factor in this aspect of the design.

HYDROLOGIC DESIGN

The most important consideration in the design of a rainfall harvesting system is the dependability of the water supply. The storage tank must be large enough to carry a supply of water through a period of no rainfall. If this should prove too costly, the storage tank is designed for some dependability level or probability of having water in storage.

The volume of the storage tank for a selected probability of having water in storage is also affected by the size of the catchment area. A method for properly sizing the catchment area and tank volume for a given water use rate and probability level is presented in this discussion.

Runoff from an impervious catchment is assumed to be equal to rainfall. Therefore, the runoff frequency distribution characteristics can be determined from a study of rainfall frequency characteristics. The 75-year record (1894 to 1968) of rainfall at Stillwater will be used to demonstrate the design procedure.

The probability of the occurrence of periods of minimum rainfall must be determined first. A method developed by Jeppson[5] was adapted to this use. It is outlined in the following steps:

1. Tabulate the monthly rainfall.
2. Calculate successive average monthly rainfalls for selected periods. Those chosen for this study were 2, 4, 6, 8, 10, 12, 15, 18, 21, 24, 27, 30, 33, 36, 39, 42, 45, 48, 54, 60, 72, and 84 months.
3. Array the period monthly averages in descending order.
4. Calculate the probability of occurrence of a given average by dividing its rank by the number of quantities in the array plus 1. Expressed algebraically:

$$P = \frac{m}{N + 1}$$

where P = probability, m = rank, and N = number of quantities.

5. Plot the average monthly rainfall versus its probability on probability paper. The plotting for the 2-month period is shown on figure 7.
6. Determine monthly rainfall averages for selected probabilities for the chosen periods from the plotted frequency curves. In this study the 80, 90, 95, 98, 99, and 99.5 percent probabilities were used.
7. Calculate the total rainfall for each chosen period for each selected probability level by multiplying the monthly average by the number of months in the period. This total will be the minimum rainfall expectancy for the period.
8. Plot the total rainfall calculated in step 7 against the length of the period in months. This plotting is the accumulated minimum rainfall (or runoff since the two are assumed equal) at the selected probability level for any given period of time. The slope of the curve at any point on it is the rate of accumulation. Figure 8

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[5] Jeppson, Roland W. Frequency analyses and probable storage requirements by frequency mass curve methods. Utah Water Research Laboratory, College of Engineering, Utah State University, Logan, Utah, 45 pp., illus. 1967.

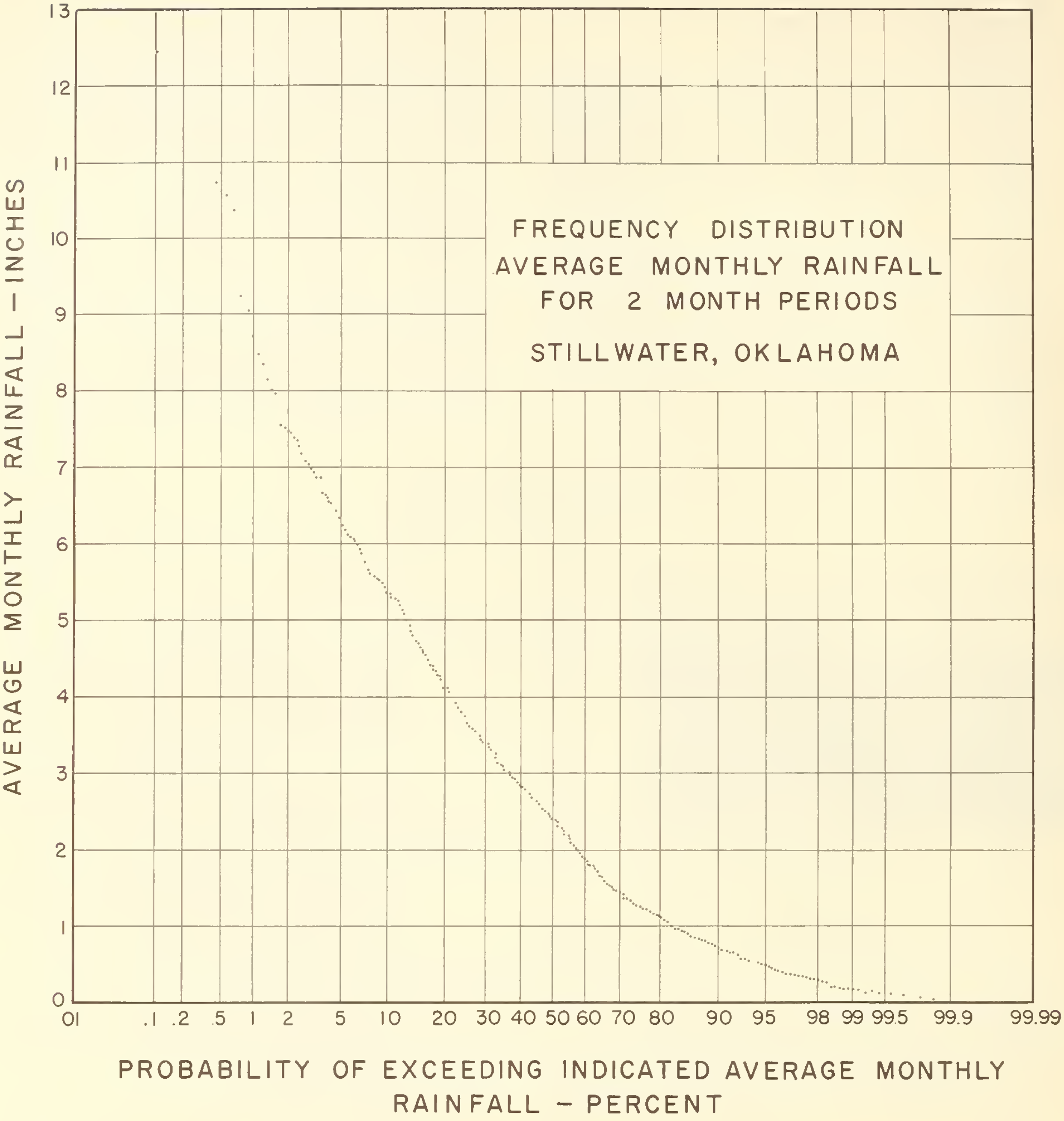

Figure 7.–Frequency distribution of average monthly rainfall for 2-month periods. Based on 75-year record at Stillwater, Okla.

is the plotting for the 99.5 percent probability. The annual rainfall cycle is evident in the peaks at 12 and 24 months.

9. Determine the storage volume required to maintain a withdrawal rate through a drought period. This is done by plotting a straight line on the accumulated runoff curve (fig. 8) at a slope equal to the withdrawal rate. Two examples are shown on figure 8, one for 2.15 inches per month and the other for 1.0 inch per month. The storage required is given by the maximum departure of the withdrawal accumulation line from the runoff accumulation line. Thus to withdraw 2.15 inches per month and be assured of having water 99.5 percent of the time requires a storage volume of 15.20 inches. At a withdrawal rate of 1.0 inch per month, the related volume is only 2.35 inches.

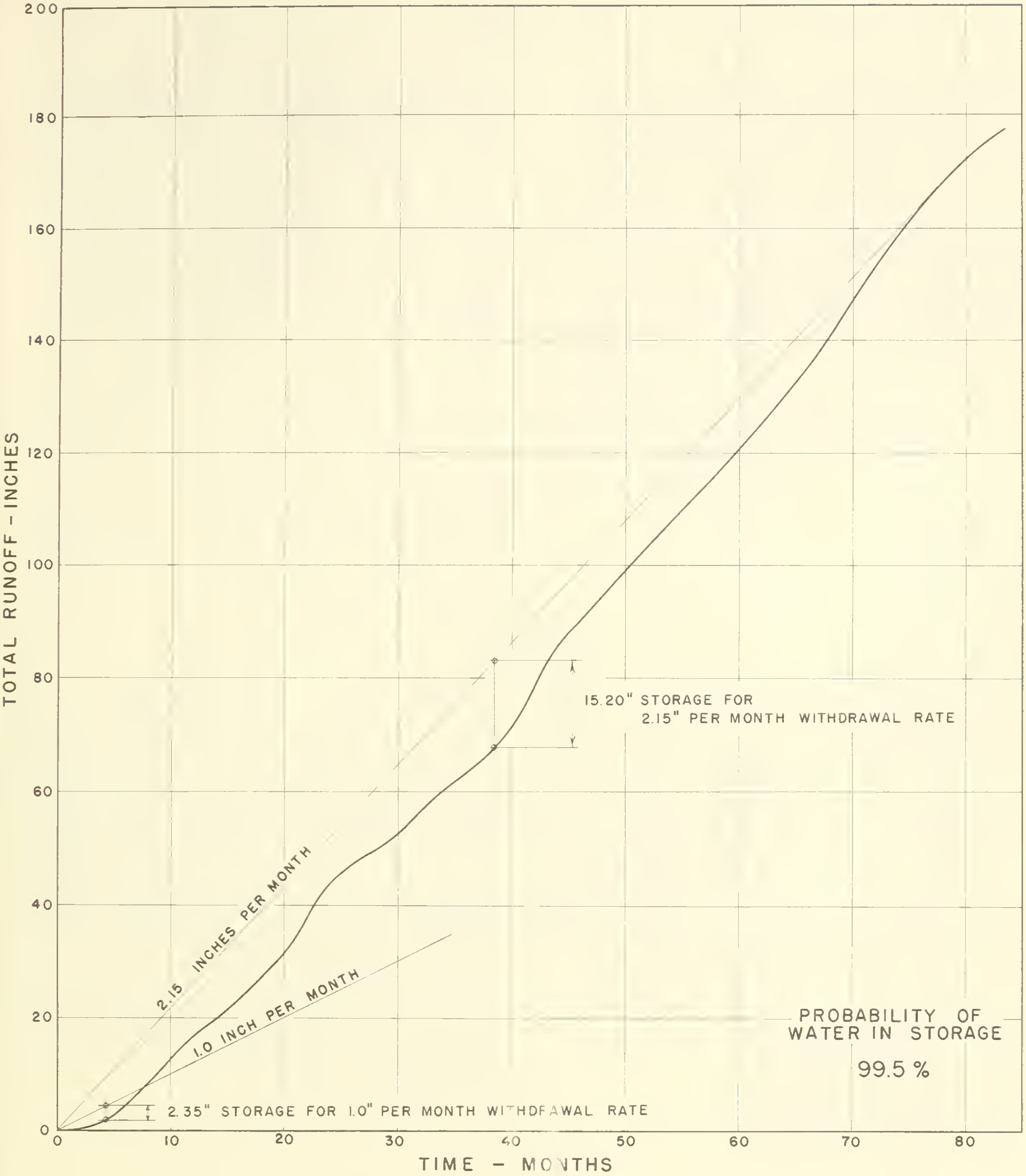

Figure 8.–Accumulated runoff which can be exceeded 99.5 percent of the time versus accumulated time for Stillwater, Okla.

The completion of the nine steps provides the information needed to design a rain harvesting system for water supply. However, withdrawal rates in inches per month need to be converted to water use rates in gallons per day, and this requires consideration of the catchment area, which is usually expressed in square feet. The storage volumes in inches need to be translated into gallons, and again this conversion is a function of the catchment area. A diagram (fig. 9) has been devised to provide a ready solution to these problems. Its use will be illustrated with an example.

Assume that the need is for 200 gallons of water a day and that a 99 percent probability of having water is acceptable. The catchment area and storage volume need to be determined. A solution is shown on figure 9 which yields 7,000 square feet for the catchment area and 16,700 gallons for the storage tank. It is evident from an inspection of the diagram that other solutions are possible. The procedure then should be to determine a number of solutions and choose the most economic one. If excavated, lined, and covered pits are used for storage, any size tank can be constructed. However, if a prefabricated tank is to be used, choice of sizes will be limited, and the solution should be to find the corresponding catchment area. There will be but one "best" size catchment area for each size of storage tank.

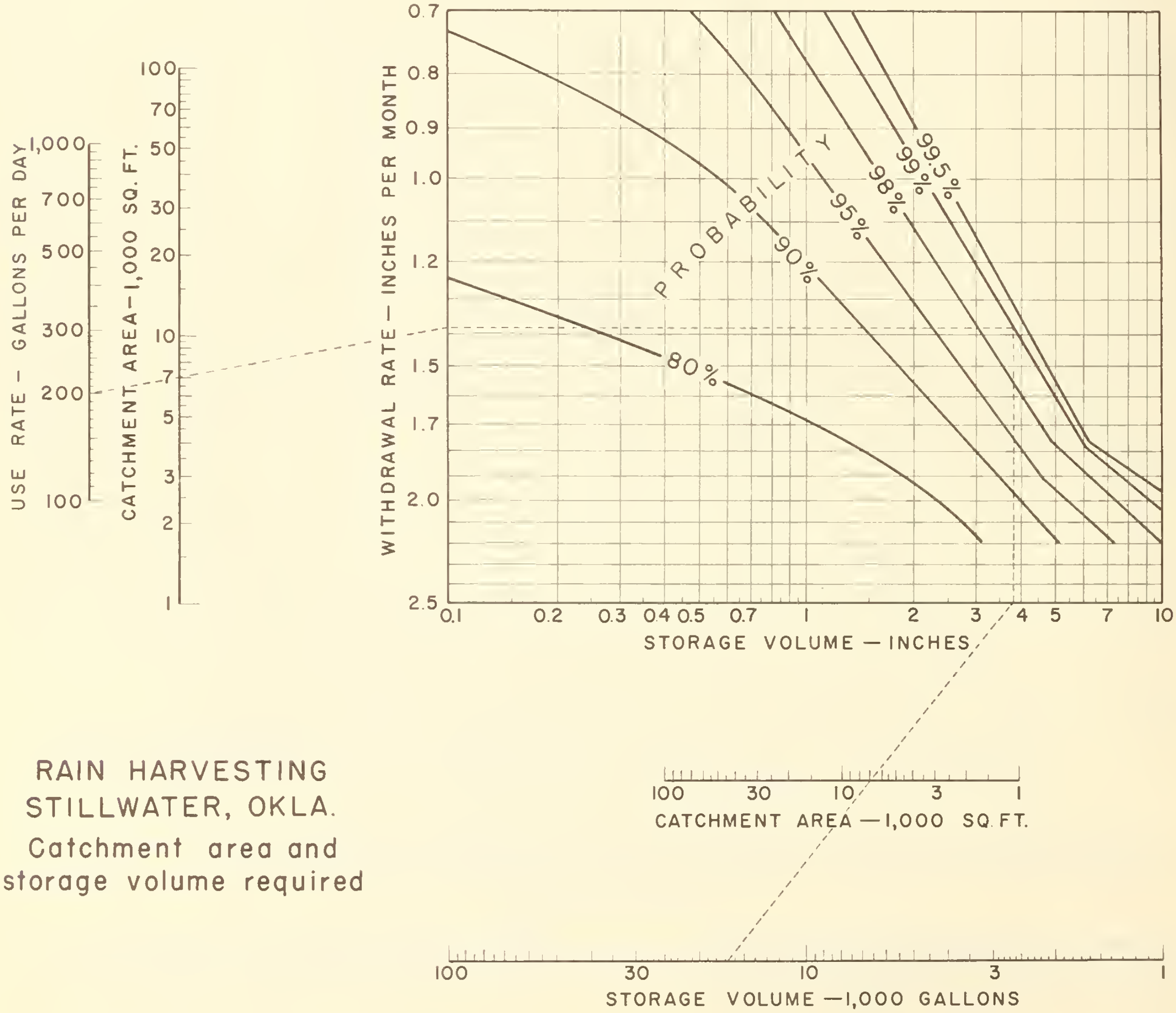

Figure 9.–Catchment areas and storage tank volumes for rain harvesting systems for the Stillwater, Okla., area. Use rate and probability are the parameters.

MATERIALS

Catalogs and other information supplied by manufacturers of rainfall harvesting systems or water storage tanks show steel and Fiberglass[6] as well as butyl rubber components. In addition to these prefabricated components, asphalt and Portland cement concrete can be considered for the construction of a rainfall harvesting system. The choice of material for a system should be decided by the arrangement that would result in the lowest cost per unit of water delivered. This cost should include costs of maintenance, depreciation, and installation as well as those of the components or materials. Since conditions will vary greatly from location to location, no general recommendations for a best material can be made. As long as the catchment area delivers all the rainfall it receives to the storage tank and as long as the storage tank does not leak or permit evaporation, any material can be used. It might be desirable, in some situations, to use a tank of one material and a catchment area of another.

Manufacturers' literature shows tanks available in sizes up to 50,000 gallons. Catchment areas up to 10,000 square feet in one large sheet are provided by some manufacturers, and others offer strips of membrane which can be cemented together to form the sheet of desired size. The selection of components, therefore, should begin with the tank and then proceed to the selection of the catchment area of the proper size. Figure 10 has been developed for the Stillwater vicinity and shows for a 99 percent probability of having water the relationship of withdrawal rate in gallons per day, volume of the storage tank in gallons, and the minimum catchment area in square feet to supply the needed water. If a catchment area larger than the minimum size must be purchased, the effect will be to supply more water than the requirement.

SUMMARY

A butyl rubber rainfall harvesting system was installed near Stillwater, Okla., and observations were made of its performance. Runoff volumes were equal to or slightly greater than volumes calculated as the product of rain gage measurements of rainfall depth and the area of the catchment. Runoff rates were approximately equal to the average 5-minute rainfall intensities for corresponding periods.

The catchment area cover billowed when high winds occurred during the first year, but this has not been observed in recent years. Animals tore some holes in the catchment area cover, but these were satisfactorily patched. The cover was still in good condition at the time this report was written.

Water delivered was low in minerals but was contaminated with feces and not fit for human consumption unless treated.

A hydrologic design method for the selection of storage tank size and catchment area is based on an analysis of frequency of occurrence of minimum rainfall amounts for periods ranging from 2 to 84 months. Design diagrams facilitate the determination of tank sizes and catchment areas for various water use rates and probability levels of having water available.

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[6] Trade names are used in this publication solely for the purpose of providing specific information. Mention of a trade name does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture or an endorsement by the Department over other products not mentioned.

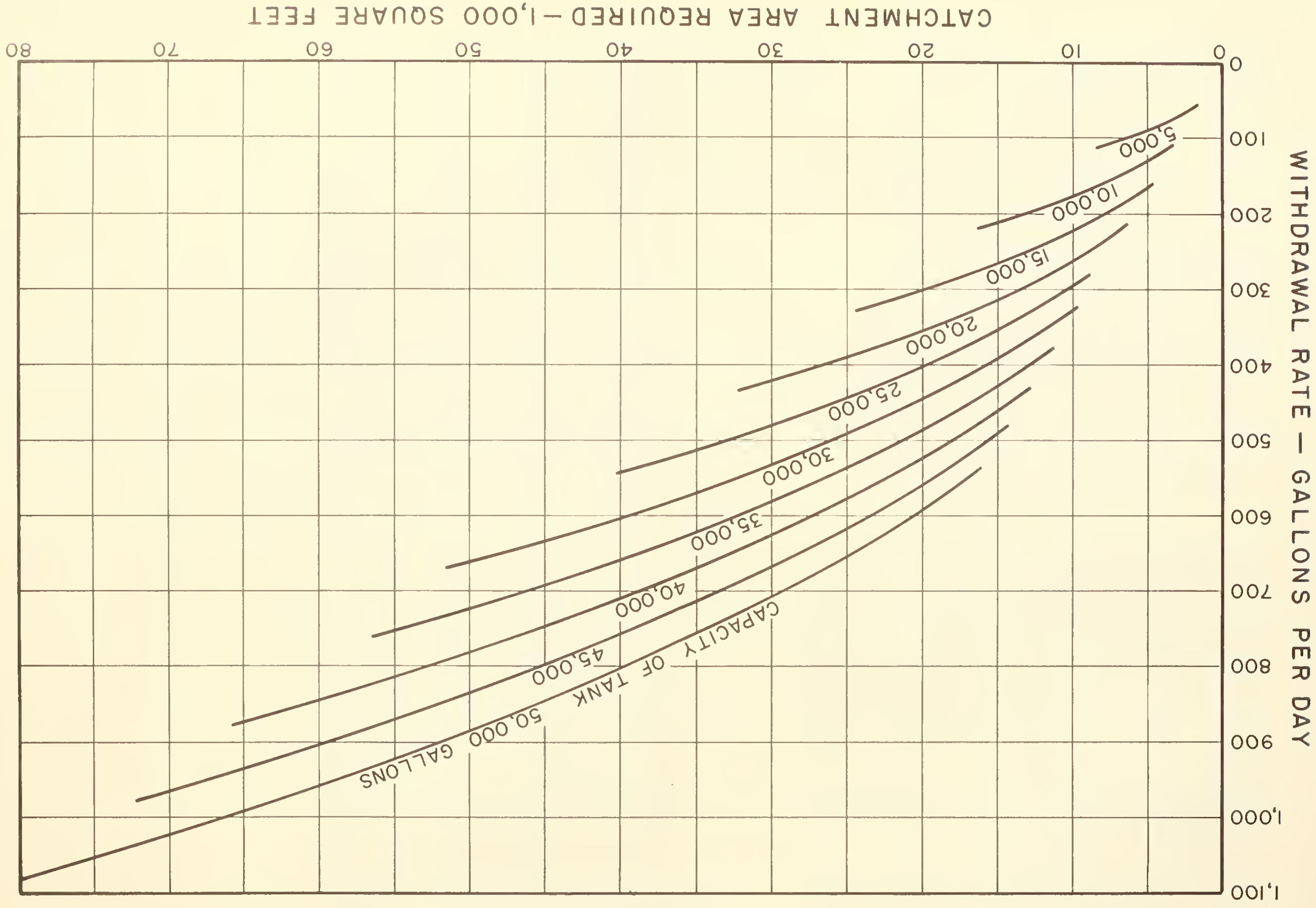

Figure 10.–Rain trap catchment area versus daily water withdrawal rate for various sizes of storage tanks and for a probability of having water 99 percent of the months. These data are for application to the vicinity of Stillwater, Okla., only.

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